

## CLUES TO THE STAR FORMATION IN NGC 346 ACROSS TIME AND SPACE \*

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### ABSTRACT

We have studied the properties of the stellar populations in the field of the NGC 346 cluster in the Small Magellanic Cloud, using the results of a novel self-consistent method that provides a reliable identification of pre-main sequence (PMS) objects actively undergoing mass accretion, regardless of their age. The 680 identified bona-fide PMS stars show a bimodal age distribution, with two roughly equally numerous populations peaked respectively at  $\sim 1$  Myr, and  $\sim 20$  Myr. We use the age and other physical properties of these PMS stars to study how star formation has proceeded across time and space in NGC 346. We find no correlation between the locations of young and old PMS stars, nor do we find a correspondence between the positions of young PMS stars and those of massive OB stars of similar age. Furthermore, the mass distribution of stars with similar age shows large variations throughout the region. We conclude that, while on a global scale it makes sense to talk about an initial mass function, this concept is not meaningful for individual star-forming regions. An interesting implication of the separation between regions where massive stars and low-mass objects appear to form is that high-mass stars might not be "perfect" indicators of star formation and hence a large number of low-mass stars formed elsewhere might have so far remained unnoticed. For certain low surface density galaxies this way of preferential low-mass star formation may be the predominant mechanism, with the consequence that their total mass as derived from the luminosity may be severely underestimated and that their evolution is not correctly understood.

*Subject headings:* stars: formation – stars: pre-main-sequence – stars: mass function – Magellanic Clouds

### 1. INTRODUCTION

With over 30 O-type stars amongst its denizens (Massey, Parker & Garmany 1989; Evans et al. 2006), the NGC 346 cluster is the site of most intense star formation in the Small Magellanic Cloud (SMC) as well as one of the most active in the Local Group. The massive young stars in NGC 346 are responsible for the ionisation of the surrounding N 66 nebula, the largest HII region in the SMC (Henize 1956). The location of NGC 346 and N 66 in the SMC, their geometry and the limited amount of foreground extinction have made these regions an ideal place to study the effects of massive objects on the surrounding medium, including whether they can effectively trigger the formation of new generations of stars, as some theories of sequential star formation suggest (e.g. Elmegreen & Lada 1977).

Over the past 20 years, many authors have attempted to give an answer to these questions. Massey, Parker & Garmany (1989) conducted a photometric and spectroscopic study of NGC 346, revealing not only 33 O-type stars (1/3 of which earlier than O6.5), but also several lower-mass stars ( $\sim 15 M_{\odot}$ ) forming a distinct subgroup  $\sim 2'6$  to the SW of the centre and with an estimated age of order 15 Myr. The age difference with respect to the O-type stars led these authors to suggest that sequential star formation might have occurred in the region.

Using near- and mid-infrared as well as CO sub-millimetre observations, Contursi et al. (2000) and Rubio et al. (2000) were able to identify several embedded sources in the bar making up the body of NGC 346, corresponding to strong emission peaks whose presence may reveal recent and/or ongoing star formation. However, while the peak corresponding with the central NGC 346 cluster contains unreddened stars, all other peaks are affected by higher reddening, suggesting that the interstellar material has not been completely ejected and that they could be in a younger stage of evolution. Since the more reddened peaks appear to be located farther away from the central cluster, these authors have suggested that star formation might have taken place in a sequential way along the bar.

More recent observations with the Hubble and Spitzer Space Telescopes have resolved the mid-infrared emission peaks, revealing that they are compact clusters made up of a multitude of pre-main sequence (PMS) stars (Nota et al. 2006; Sabbi et al. 2007; Hennekemper et al. 2008) and young stellar objects (YSO; Bolatto et al. 2007; Simon et al. 2007). Hennekemper et al. (2008) performed a detailed analysis of the locations of these PMS stars in the colour–magnitude diagram (CMD), which they compare with the PMS isochrones of Siess et al. (2000) taking into account the effects of differential reddening, binarity and variability on the age determination. They conclude that, depending on the amount of reddening present in the field, the observed broadening of the positions of these PMS objects in the CMD can be compatible with both a single star formation episode some  $\sim 10$  Myr ago or with two episodes about 5 and 10 Myr ago. Nevertheless, even in this latter case, the lack of a correlation between the estimated ages and the positions of the objects in the field led Hennekemper et al. (2008) to conclude that there is no obvious signature of sequential star formation in this region.

In a subsequent study by the same team, Gouliermis et al. (2008) suggest that signs of sequential star formation might

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actually be present. They propose a scenario in which the birth of the three young star clusters on the arc-like structure was triggered by the winds of the massive progenitor of SNR B0057–724 located at the centre of the arc,  $\sim 20$  pc away. Gouliermis et al. (2008) also suggest that, in a similar manner, the powerful winds of the OB stars at the centre of NGC 346 are shaping a dusty arc feature to the south and southwest of the association. On the other hand, as we will show in Section 3, the dusty arc feature appears to be  $\sim 20$  Myr old and little or not at all affected by the presence of the OB stars in the centre (Smith 2008), suggesting that there is no causal connection between the arc and the massive stars at the centre of NGC 346.

The weak side of all these studies is that they are mostly qualitative. They are primarily based on the analysis of the spatial distribution of the objects and on the morphology and geometry of the features present in the field. However, they do not take into account the actual ages of the low-mass stars that are needed to establish whether there are dependencies and correlations amongst the stellar generations that have formed in the recent past in these regions.

An improvement in this sense is offered by the recent work of Cignoni et al. (2011). Using a classical synthetic CMD procedure, they concluded that NGC 346 has experienced different regimes of star formation, including a dominant and focused “high density mode”, which according to these authors led to the formation of rich and massive sub-clusters hosting both PMS and massive MS stars, and a subsequent diffuse “low density mode”, characterised by the presence of sub-clusters hosting PMS stars only. These different modes of star formation can have an impact on the shape of the mass function (MF), as we discuss further in Section 3 and 4. Cignoni et al. (2011) suggest that the richest sub-clusters formed  $\sim 6$  Myr ago, with an apparent remarkable synchronisation, while star formation in the sub-clusters mainly composed of PMS stars appears to have started  $\sim 3$  Myr ago, following a multi-seeded spatial pattern.

Even in works of this type, however, the available age range for low-mass stars is limited to the youngest PMS objects ( $\lesssim 5$  Myr). This is because ages are based on the comparison of the observations with theoretical evolutionary tracks in the Hertzsprung–Russell (H–R) diagram, and at older ages the isochrones become too close to the very populous main sequence (MS) of field stars to provide reliable results.

Actually, the presence of distinctive emission features in the spectra of PMS stars with ages up to  $\sim 30$  Myr, due to the accretion process to which they undergo, allows us to efficiently and securely detect and identify all objects of this type in a stellar field, regardless of their age and of their position in the H–R diagram. Building on the work of Romaniello (1998) and of Panagia et al. (2000), De Marchi, Panagia & Romaniello (2010, hereafter Paper I) showed that through a suitable combination of broad- and narrow-band photometry it is also possible to derive the mass accretion rate of these objects, with an accuracy comparable to that allowed by spectroscopy. In a companion paper (De Marchi et al. 2011; hereafter Paper II), we applied the method developed in Paper I to the high-quality HST photometry of NGC 346 (Sabbi et al. 2007) and were able to identify two distinct generations of bona-fide PMS stars (about 700 objects) with a clearly bimodal age distribution in the range from  $\lesssim 1$  Myr to  $\sim 30$  Myr. In this work we use the accurate physical parameters that we have measured in Paper II and correlate them with the spatial distribution of these objects. The availability of accurate ages

for such a large number of stars across the field is the key element that was missing in previous studies of NGC 346 and allows us for the first time to study how star formation has proceeded in this area over the past  $\sim 30$  Myr.

The paper is organised as follows: in Section 2 we briefly summarise the results of Paper II and presents the relevant observational material. Section 3 compares the spatial distribution of the two generations of PMS stars to one another and to that of young massive stars present in the field. In Section 4 we look at how the shape of the stellar mass function changes across the field. In Section 5 we discuss the possible consequences of different processes operating for high mass and low mass star formation on the study of galaxies and the determination of their star formation rates. A summary of the most important conclusions of the paper is offered in Section 6.

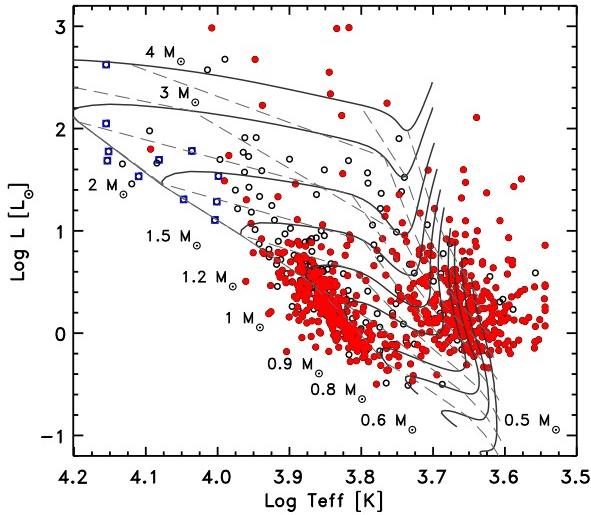
## 2. PRE-MAIN SEQUENCE STARS IN NGC 346

In Paper II, we have studied the properties of the stellar populations in a field  $200'' \times 200''$  around the centre of NGC 346, making use of observations collected with the Advanced Camera for Surveys on board the Hubble Space Telescope (details on the observations and on the photometric analysis of the data can be found in Nota et al. 2006 and Sabbi et al. 2007). We refer the reader to Paper II for a detailed description of the analysis of the stellar populations in this field and of the determination of their properties. However, for convenience, we offer hereafter a brief summary of the main results that are most relevant to this paper.

Thanks to a novel, self-consistent method developed in Paper I, it is possible to reliably identify PMS stars undergoing active mass accretion, regardless of their age. The method, fully described in Paper I and II, does not require spectroscopy and combines broad-band  $V$  and  $I$  photometry with narrow-band  $H\alpha$  imaging to detect all stars with excess  $H\alpha$  emission while simultaneously providing an accurate measure of their accretion luminosities  $L_{\text{acc}}$  and mass accretion rates  $\dot{M}_{\text{acc}}$ .

The application of this method to the NGC 346 observations allowed us to reveal 791 PMS candidates, namely objects with  $H\alpha$  excess above the  $4\sigma$  level with respect to the reference provided by normal cluster stars observed in the same bands. The average  $H\alpha$  luminosity of these PMS candidates is  $2.7 \times 10^{31} \text{ erg s}^{-1}$  or  $\sim 10^{-2} L_{\odot}$ . In order to avoid possible contamination due to objects with significant chromospheric activity, we retained as bona-fide PMS stars only those with a large equivalent width of the  $H\alpha$  emission line,  $W_{\text{eq}} < -20 \text{ \AA}$  for stars with  $T_{\text{eff}} < 10000 \text{ K}$  or  $W_{\text{eq}} < -50 \text{ \AA}$  for hotter stars (note that, as customary, a negative equivalent width is used for emission lines). A total of 694 objects satisfy these conditions.

A colour–magnitude diagram showing the positions of these objects in the observational plane ( $V$  vs  $V-I$ ) is provided in Paper II. In Figure 1 we show the locations of these objects in the H–R diagram (thick dots, in red in the online version), compared with the PMS evolutionary models of the Pisa group (Degl’Innocenti et al. 2008; Tognelli, Prada Moroni & Degl’Innocenti 2011) for metallicity  $Z = 0.002$ . As noted in Paper II, although this metallicity is at the lower end of the currently accepted values for the SMC, ranging from  $\sim 1/5$  to  $\sim 1/8 Z_{\odot}$  (see Russell & Dopita 1992; Rolleston et al. 1999; Lee et al. 2005; Perez–Montero & Diaz 2005), it appears better suited to describe the properties of young PMS stars in this field. As Figure 1 immediately shows, there are two separate groups of objects, occupying two distinct regions



**Figure 1.** Hertzsprung–Russell diagram of the PMS candidate stars. All objects shown here have excess emission in  $H\alpha$  at the  $4\sigma$  level or higher. Those indicated with filled circles also have  $W_{eq}(H\alpha) < -20 \text{ \AA}$  or  $< -50 \text{ \AA}$  for stars hotter than  $10000 \text{ K}$ . Squares correspond to objects with  $W_{eq}(H\alpha) > -50 \text{ \AA}$  and, as such, are potential Be stars. Thick solid lines show the evolutionary tracks from Degl'Innocenti et al. (2008) for metallicity  $Z = 0.002$  and masses from  $0.5$  to  $4 M_\odot$ , as indicated. The corresponding isochrones are shown as thin lines, for ages of  $0.125, 0.25, 0.5, 1, 2, 4, 8, 16$  and  $32 \text{ Myr}$  from right to left. Note that the constant logarithmic age step has been selected in such a way that the photometric uncertainties result in even smaller uncertainties on the relative ages, typically of order  $\sqrt{2}$ . Thus, the age difference *between* the two groups of PMS stars is very significant, since the age gap between the two groups is much wider than the uncertainty on the relative ages. In fact, the age spreads *within* each group might actually be somewhat smaller than what we quote, since our interpolation procedure does not take unresolved binaries into account. Da Rio et al. (2010a) have shown that when binaries are ignored the derived age spread appears wider, although the average age itself is not affected. Therefore, the two groups of objects may be even better separated in age than our numbers imply. On the other hand, we believe that interpreting the observed broadening as an age effect is the most conservative assumption as regards our conclusions. We address the properties of these two populations in detail in Section 3.

in the diagram, one well above (or redder than) the MS and the other at the MS itself. This distinction is equally clear in the CMD shown in Paper II.

Comparison with the evolutionary tracks (solid lines, corresponding to the masses as indicated) and with the isochrones (dashed lines, for ages increasing from right to left from  $0.125 \text{ Myr}$  to  $32 \text{ Myr}$  doubling at each step) allows us to determine accurate masses and relative ages for 680 of these objects. Note that previous determinations of these parameters for candidate PMS stars in NGC 346 that made use of evolutionary models for  $Z = 0.01$  are necessarily less accurate. For the interpolation, we followed the procedure developed by Romanelli (1998), which does not make assumptions on the properties of the population, such as the functional form of the initial mass function (IMF). On the basis of the measurement errors, this procedure provides the probability distribution for each individual star to have a given value of the mass and age (the method is conceptually identical to the one presented recently by Da Rio et al. 2010a).

The masses that we obtain range from  $\sim 0.4 M_\odot$  to  $\sim 4 M_\odot$ , with an average value of  $\sim 1 M_\odot$ , whereas the ages show a clear bimodal distribution, already implicit in Figure 1, where very few objects are seen around ages of  $\sim 4 – 8 \text{ Myr}$ . Taking  $7 \text{ Myr}$  as a threshold, the PMS stars can be split into two almost equally populous groups. One group comprises 350 objects younger than  $7 \text{ Myr}$  (hereafter called “younger PMS stars”), with a median age of  $\sim 1 \text{ Myr}$  (formally  $0.9 \text{ Myr}$ ) and a distribution ranging from  $0.3 \text{ Myr}$  to  $3.1 \text{ Myr}$ , respectively the 17 and 83 percentiles. The other group contains 330 objects older than  $7 \text{ Myr}$  (hereafter called “older PMS stars”), with a median age of  $\sim 20 \text{ Myr}$  (formally  $19.7 \text{ Myr}$ ) and a distribution ranging from  $12.5 \text{ Myr}$  to  $26.5 \text{ Myr}$  (17 and 83 percentiles, respectively). In fact, the latter value should be considered a lower limit to the age of

these objects. Regardless of the statistical approach that one follows, when a star in the H–R diagram is closer to the zero-age MS than its photometric errors, only a lower limit to its age can be derived, since the long tail of the distribution function makes all older ages in principle equally likely.

As discussed in Paper I, our age uncertainties are typically less than a factor of two (hence the choice of the spacing between isochrones in Figure 1) and this includes systematic differences arising because of the use of models that might not properly describe the stellar population under study (e.g. because of the wrong metallicity) and from differences between models of various authors. Yet for a given set of models, our photometric uncertainties result in even smaller uncertainties on the relative ages, typically of order  $\sqrt{2}$ . Thus, the age difference *between* the two groups of PMS stars is very significant, since the age gap between the two groups is much wider than the uncertainty on the relative ages. In fact, the age spreads *within* each group might actually be somewhat smaller than what we quote, since our interpolation procedure does not take unresolved binaries into account. Da Rio et al. (2010a) have shown that when binaries are ignored the derived age spread appears wider, although the average age itself is not affected. Therefore, the two groups of objects may be even better separated in age than our numbers imply. On the other hand, we believe that interpreting the observed broadening as an age effect is the most conservative assumption as regards our conclusions. We address the properties of these two populations in detail in Section 3.

Besides the age and mass and  $H\alpha$  luminosity already mentioned, another other important physical parameter that we derived in Paper II for these objects is the mass accretion rate  $\dot{M}_{acc}$ , which has a median value of  $3.9 \times 10^{-8} M_\odot \text{ yr}^{-1}$ . This value is about 50 % higher than that measured in Paper I for a population of 133 PMS stars in the field of SN 1987A, owing to the much younger median age of PMS objects in NGC 346. In fact, the large size of our PMS sample and its spread in mass have allowed us to study the evolution of the mass accretion rate as a function of stellar parameters and to conclude that  $\log \dot{M}_{acc} \simeq -0.6 \log t + \log m + c$ , where  $t$  is the age of the star,  $m$  its mass and  $c$  a quantity that is higher at lower metallicity (see Paper II for details).

### 3. STAR FORMATION ACROSS TIME AND SPACE

In this section we use the information on the physical parameters of PMS stars of various masses and ages to study how star formation has proceeded in NGC 346 over the past  $\sim 30 \text{ Myr}$ , since this is the time span that we can effectively and accurately probe with our method.

#### 3.1. Multiple stellar generations

As mentioned above, the distribution of our bona-fide PMS stars in the H–R diagram reveals a shortage of objects with ages around  $\sim 4 – 8 \text{ Myr}$ , suggesting a likely gap or lull in star formation at that time. The presence of two so clearly distinct groups of stars with  $H\alpha$  excess can only be interpreted as the result of distinct star formation episodes. Hillenbrand et al. (2008) and Hillenbrand (2009) have argued that random luminosity spreads apparent in the H–R diagram of star forming regions and young clusters are often erroneously interpreted as true luminosity spreads and taken as indicative of true age spreads. This is clearly not the case here, since no random spread in the luminosity of a single age population could produce such a distinctive bimodal distribution in the H–R diagram.

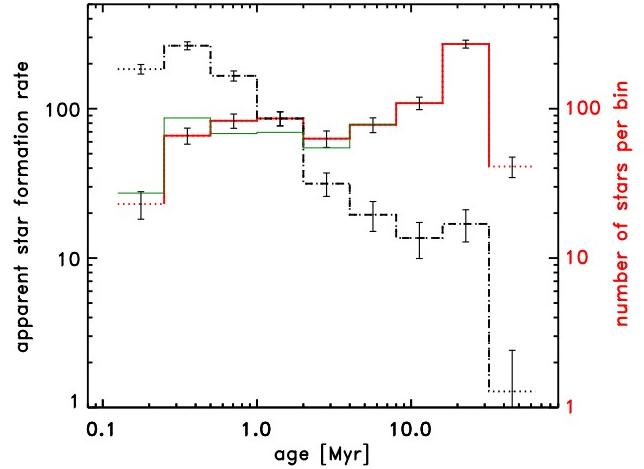
On the other hand, some of the objects that we label older PMS stars could actually be very young stars with a circumstellar disc seen at high inclination ( $> 80^\circ$ ). Objects of this type would appear bluer than their photospheric colour due to light scattering on the circumstellar disc. However, they would also be several magnitudes fainter than their photospheric brightness due to extinction caused by an almost edge-on disc. According to the models of Robitaille et al. (2006) for the spectral energy distribution of young stars seen at various viewing angles, objects of this type can only account for a few percent of the total young population. Furthermore, as we will show in Section 3.2, the spatial distribution of the stars with H $\alpha$  excess close to the MS is remarkably different from that of the younger PMS stars, and this should not be the case if these were all objects of the same type simply viewed at different inclinations. Therefore the vast majority of stars with H $\alpha$  excess near the MS must be intrinsically older.

In a forthcoming paper (De Marchi, Guarcello & Panagia, in preparation) we will address in detail the role played by circumstellar discs seen at high inclination, which can undoubtedly account for a small fraction (< 5 %) of our sample. That work will discuss in detail the theoretical implications that such a geometry can have on the extinction and scattering of the light of the central object and will address the specific case of NGC 6611 in the Eagle Nebula, where like in NGC 346 a population of older ( $\sim 10$  Myr) PMS stars is also present.

As regards the age distribution of PMS stars in NGC 346, a histogram is shown in Figure 2, where PMS ages are binned using a constant logarithmic step (a factor of 2) that better reflects the relative age uncertainties stemming from the comparison of model isochrones with the actual data. The solid line in Figure 2 gives the number of stars inside each age bin as a function of time, whereas the dot-dashed line provides an apparent value of the star formation rate, in units of stars per Myr, derived by dividing the number of objects in each bin by the width of the bin. Note that at the extremes of the distribution it becomes more difficult to assign an age to the stars, thus the first and last bin are drawn with a dotted line to indicate a larger uncertainty. In particular, as mentioned above, for stars that in the HR diagram are closer to the MS than their photometric error, the age that we provide is in practice a lower limit to the true age. This is due to the fact that the distribution function is characterised by such an extended tail towards older ages that all ages older than the value that we provide are virtually equally likely.

Also the dot-dashed line necessarily represents a lower limit to the star formation rate. In this case, the reason is not the age uncertainty but the fact that we consider exclusively the number of detected PMS stars in the range  $0.4 - 4.0 M_\odot$  that at the time of the observations had H $\alpha$  excess emission at the  $4\sigma$  level or above. One limitation is caused by photometric incompleteness at low masses, which makes it more difficult to detect faint PMS stars in crowded environments. Another effect is the uncertainty on the fraction of PMS stars that at any given time show excess H $\alpha$  emission. For younger PMS stars ( $\lesssim 8$  Myr), whose position in the H-R diagram is well separated from that of field MS stars, this fraction can be estimated from the ratio of stars with and without H $\alpha$  excess in the same region of the diagram. The data show that at the time of the observations this ratio was  $0.28 \pm 0.04$  (see also Paper II).

The thin solid line in Figure 2 (green in the online version) shows the age distribution of all stars in the H-R diagram younger than 8 Myr, shifted vertically by  $-0.56$  dex (corre-

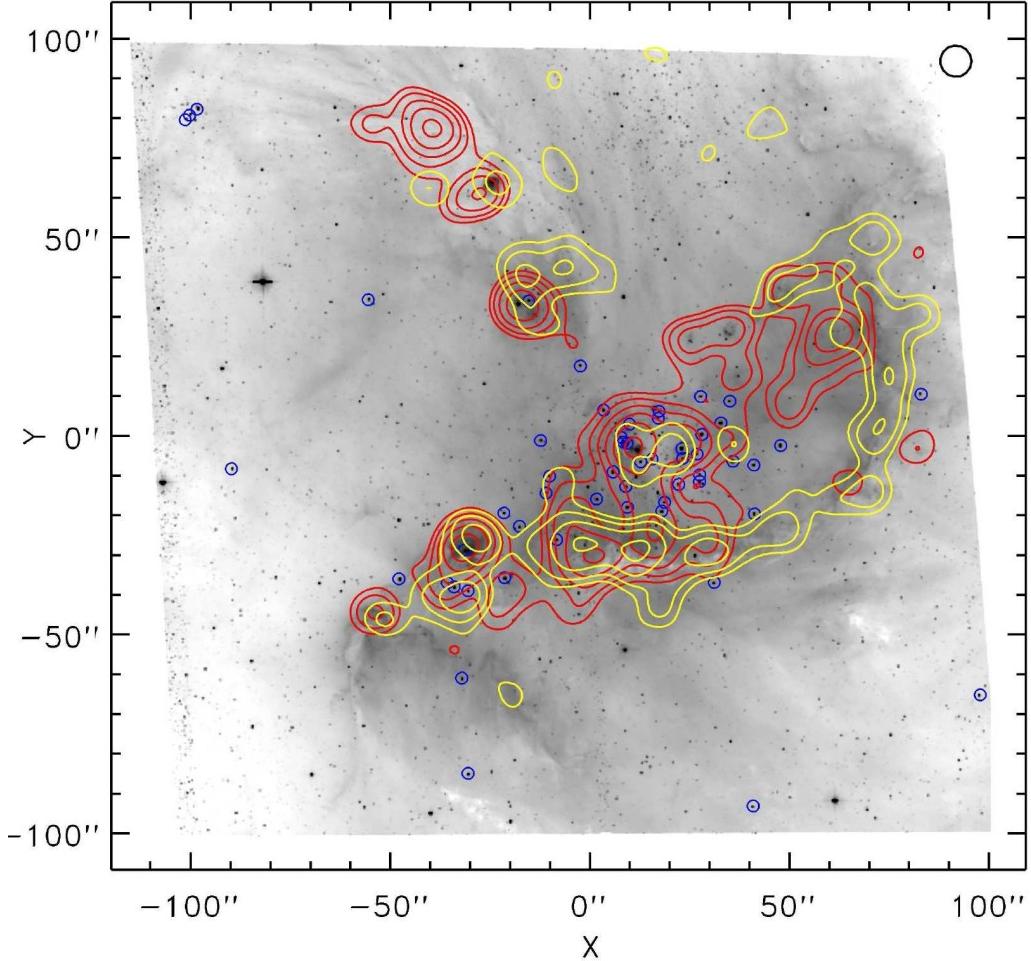


**Figure 2.** Histograms showing the number of stars per age bin (thick solid line) and the apparent star formation rate (dot-dashed line) as a function of age. Only bona-fide PMS stars (i.e. objects with H $\alpha$  excess emission at the  $4\sigma$  level or above at the time of the observations) in the range  $0.4 - 4 M_\odot$  are considered in this figure, so the dot-dashed line provides a lower limit to the true star formation rate. The thin solid line shows the age distribution of all stars (i.e. also those without H $\alpha$  excess emission), but only up to ages of 8 Myr, since older objects cannot be distinguished from field MS stars. The thin solid histogram is shifted vertically by  $-0.56$  dex and appears in excellent agreement with the thick solid histogram.

sponding to a factor of 0.28), and is in excellent agreement with the histogram of bona-fide PMS stars. However, it is presently not known how this ratio would change at older ages, and it is also expected to depend on the mass of the stars, so at this stage it is only possible to set a lower limit to the true star formation rate. Near the peak of the distribution, at  $\sim 0.4$  Myr, this limit corresponds to  $\sim 200 M_\odot \text{ Myr}^{-1}$  (the median mass of those objects is  $\sim 0.7 M_\odot$ ), while at  $\sim 25$  Myr it drops by an order of magnitude to  $\sim 20 M_\odot \text{ Myr}^{-1}$  (median mass  $\sim 1 M_\odot$ ).

At face value, the star formation strength for stars in the range  $0.4 - 4.0 M_\odot$  thus appears to be much higher in the present burst than in the one that was active  $\sim 10 - 30$  Myr ago and might have ended  $\sim 8$  Myr ago, while the total integrated output (i.e. the total number of stars, as shown by the thick solid histogram) in the two episodes is rather similar. However, there are important selection effects that one must consider. As mentioned above, one effect is the fraction of PMS stars with H $\alpha$  excess, which most likely varies throughout the PMS phase, making it more difficult to compare the number of younger and older PMS stars to one another. Another problem is that, while the previous burst has certainly ended, the current one might still continue for a long time, thus making it hard to predict how many stars will eventually be formed. Finally, the accuracy on relative ages being at best of order a factor of  $\sqrt{2}$ , it is not possible to say exactly how long the previous burst lasted nor how many short bursts took place in the time frame covered by one age bin. This carries the implication that, if there was just one short burst, the star formation strength might have been comparable to or even higher than that of the current episode.

The results of our quantitative age analysis on the star formation efficiency in this field are still necessarily tentative, but it will be possible to lift at least some of the uncertainties plaguing this picture through a systematic comparison of different star forming clusters in similar states of evolution that



**Figure 3.** The contour lines show the spatial density distribution of young ( $< 7$  Myr; red) and old ( $> 7$  Myr; yellow) PMS stars in NGC 346, overlaid on a negative H $\alpha$  image of the region. The (0,0) position in this figure corresponds to RA=0<sup>h</sup>59<sup>m</sup>8<sup>s</sup>, DEC=−72°10'32" (J2000), while North is up and East to the left. The contour plots have been obtained after Gaussian smoothing with a beam size of  $\sigma = 4''$ , as indicated by the circle in the upper right corner. Blue circles correspond to young ( $< 7$  Myr) massive stars brighter than  $\sim 2 \times 10^4 L_\odot$ . The contour levels have a logarithmic spacing of  $\sim 0.17$  dex (or a factor of 1.5). The lowest level corresponds to a density of 0.033 stars per arcsec $^2$ , equivalent to twice the average density of PMS stars in this field. The highest contour level for old PMS stars corresponds to 0.11 stars per arcsec $^2$  and that for young PMS stars to 0.25 stars per arcsec $^2$ .

we plan to conduct in the future. On the other hand, having established that there are at least two star formation episodes in NGC 346, separated by  $\sim 10$  Myr or more, we still can study whether they are independent of one another or appear to be causally connected.

### 3.2. Looking for spatial correlations: contour plots

We compare in Figure 3 the spatial density distributions of the younger and older PMS populations by means of contour lines with logarithmic scaling, overlaid on a H $\alpha$  image of NGC 346. As mentioned above, the two groups include respectively 350 and 330 objects. The contour plots have been obtained after smoothing the distribution with a Gaussian beam with size  $\sigma = 4''$  or  $\sim 1.2$  pc, as indicated by the circle in the upper right corner of the figure. The lowest contour level corresponds to a local density of PMS stars twice as high as the average PMS stars density over the entire field. The step between contour levels is constant and corresponds to a factor of 1.5. We also show with small circles the positions of 55 young massive stars brighter than  $\sim 2 \times 10^4 L_\odot$  and with an implied mass  $> 15 M_\odot$  (e.g. Iben 1967).

A striking feature in this figure is the difference in the spa-

tial distribution of the three types of stars. Many older PMS stars are distributed along the rim of the gas shell to the S and W of the cluster's centre (hereafter named “southern arc”) and, except for the centre itself, they appear to avoid regions where younger PMS stars are located. As for massive stars, albeit more abundant near the centre of NGC 346, they also appear at various other locations in the field that are not occupied by PMS objects.

It is interesting to compare these contour lines with the maps of mid-IR emission obtained with ISOCAM on board the Infrared Space Observatory by Contursi et al. (2000) and Rubio et al. (2000). The strong emission peaks discovered by these authors (see also Introduction) coincide with regions of recent star formation in our analysis as well, and in particular with the intensity peaks due to younger PMS stars in Figure 3 (darker contour plots, shown in red in the online version). As regards older PMS stars, including those in the southern arc, they appear projected against a background of lower IR emission. From the analysis of observations with the Spitzer Space Telescope, Simon et al. (2007) discovered in the arc a few young stellar objects of relatively high mass ( $> 4.5 M_\odot$ ). As we will show later (see Figure 4), there are indeed also some

younger PMS stars along this gas rim, but the arc appears to be mostly dominated by older PMS objects.

The careful reader could be worried that several old PMS stars seem to lie along the southern arc, since nebular emission might in principle contaminate their photometry and give us an inaccurate measurement of their H $\alpha$  excess emission. However, as already mentioned in Paper II, we have carefully inspected the images and removed from the list of bona-fide PMS stars all objects whose H $\alpha$  photometry might be contaminated by gas filaments. While it is possible that some of the H $\alpha$  emission that we detect is due to diffuse nebular emission in the HII region not powered by the accretion process (see Paper I), if the emission is extended and uniform over an area comparable to that of the point spread function, its contribution cancels out with the rest of the background when we perform the photometry (see Sabbi et al. 2007 and Paper II for details on the photometry).

Obviously, the subtraction would not work if the emission were not uniform, as for example in the case of a filament that projects over the star but that does not cover completely the background annulus. For this reason, after applying an unsharp-masking algorithm to highlight and sharpen the details of the H $\alpha$  frames, we have carefully inspected all sources with excess H $\alpha$  emission and have marked as suspicious and excluded from our bona-fide sample all those with filaments contamination within 0. $''$ 3 of the star, for a total of 62 objects. Although some of them might have intrinsic H $\alpha$  excess emission, we prefer to adopt a conservative approach and remove all dubious cases. A detailed example of how well this powerful technique works can be found in Beccari et al. (2010). Therefore, we are confident that the tight distribution of older PMS stars along the rim of the gas shell is not an artefact and suggests instead that these objects have very low velocities or at least a very small velocity spread.

Observed values of the velocity dispersions of stars in young clusters and associations typically fall in the range 1–10 km s $^{-1}$  (e.g. van Altena et al. 1988; Jones & Walker 1988; Mengel et al. 2009; Bosch, Terlevich & Terlevich 2009; Rochau et al. 2010). The thickness of the projected distribution of the older PMS in NGC 346 is of order  $\sim 20''$  or  $\sim 6$  pc. With a median estimated age of  $\sim 20$  Myr, this implies a small value of the projected velocity spread, namely  $\lesssim 0.5$  km s $^{-1}$ , corresponding to a three dimensional velocity dispersion of  $\lesssim 1$  km s $^{-1}$  along the gaseous rim. This picture is consistent with the very low velocity dispersion ( $< 3$  km s $^{-1}$ ) of the ionised gas measured by Smith (2008) in this field from high-resolution echelle spectroscopy. If there is a higher velocity component, it must be linked to the systematic motion of the gas shell.

The match between the location of many old PMS objects (about  $\sim 1/3$  of them) and the rim of the gas shell also suggests that the shell itself reflects the distribution of the gas out of which these stars formed and that it has not (yet) been significantly affected by the stellar winds and by the ionising radiation of the much younger massive stars at the centre of the field. Furthermore, the fact that the distribution of these massive objects and of the younger PMS stars does not appear to trace in any way the geometry of the gas shell indicates quite convincingly that we are seeing two rather different and unrelated generations of stars.

From the apparent shape of the rim of the gas shell, Gouliermis et al. (2008) recently argued that there is a relationship between the central NGC 346 cluster and the southern arc.

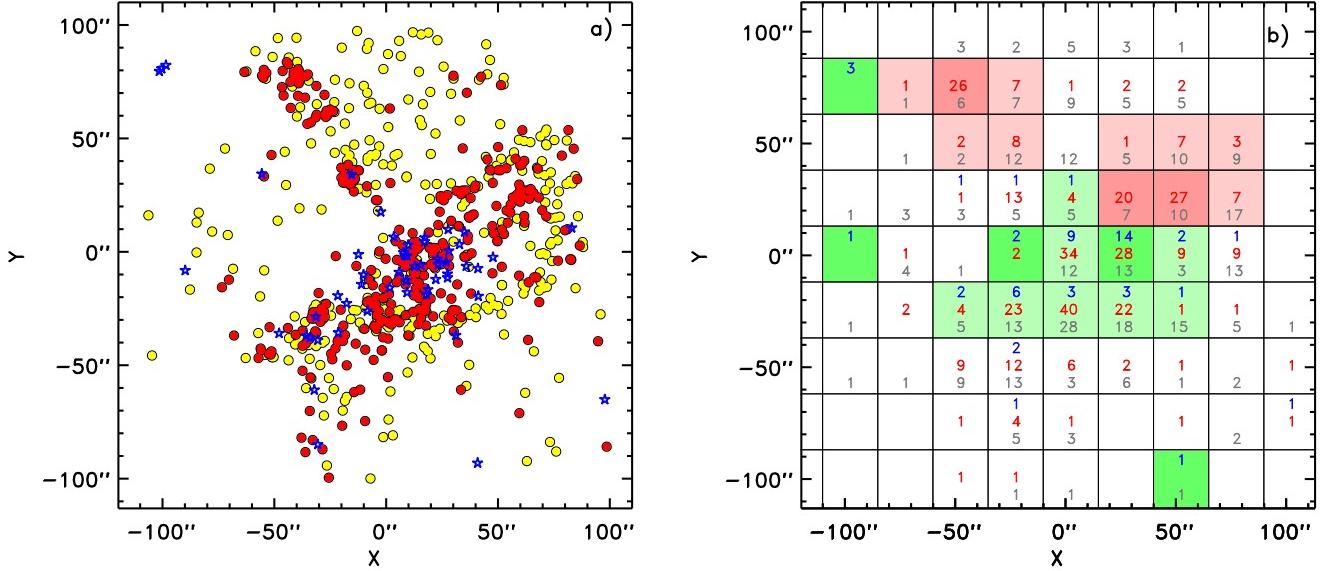
They suggested that the latter outlines the ionisation front of the cloud that is caused by the powerful stellar winds of the young massive stars at its centre. In their scenario, the photoionisation process of the central OB stars would provide the primary source of mechanical energy that triggers star formation in this region. Our analysis does not support this interpretation: not only is the rim of the gas shell unaffected by the central OB stars, but it is also much older (and it may be much farther away from the OB stars than what the projected distance might seem to suggest). This discrepancy outlines the risks of drawing conclusions on triggered star formation based primarily on the morphology of structures projected on the sky. As Watson, Hanspal & Mengistu (2010) have recently shown, only 20 % of the sample of HII regions that they studied appear to have a significant number of YSOs associated with their photodissociation fronts, implying that triggered star formation mechanisms acting on the boundary of the expanding HII region are not common.

### 3.3. Looking for correlations: number ratios

A more quantitative characterisation of the relative distribution of younger and older PMS objects and massive stars is offered by the maps shown in Figure 4. The (0,0) position in that figure corresponds to RA=0 $^h$ 59 $^m$ 8 $s$ , DEC=−72°10'32" (J2000), with North up and East to the left. In panel a) we show all young stars using different symbols (blue pentagrams, red dots and yellow dots respectively for massive young stars, younger PMS stars and older PMS objects), whereas panel b) gives the number of stars of each type falling within cells of 25" or 7.3 pc on a side, which is the typical size of a star cluster in the Magellanic Clouds (7.7±1.5 pc; Hodge 1988).

The difference in the distribution of younger and older PMS stars already seen in Figure 3 continues to be present in Figure 4, revealing that older PMS objects are less concentrated and more widely distributed than younger stars. The other notable feature in Figure 4 (and already visible in Figure 3) is the mismatch between the positions of young massive stars and those of young PMS objects of similar age (both types of objects are younger than 7 Myr and most are not older than 3 Myr). The majority of young massive stars are clustered near the adopted centre of NGC 346, where a high concentration of young PMS stars is also seen. However, there is also a number of massive objects that are not surrounded by an overdensity of PMS stars. Similarly, many PMS objects are clustered in populous groups with no massive stars in their vicinity, although the total mass of the groups can reach  $\sim 100 M_{\odot}$  even when only considering PMS objects in the range 0.4–4  $M_{\odot}$ , once photometric completeness is taken into account. A similar situation is seen in the Cygnus X North complex (Beerer et al. 2010), where the positions of many early B-type stars (the most massive objects in the region) do not coincide with those of young star clusters of similar age.

These differences can be easily quantified by using the star numbers shown in the cells of Figure 4b. The numbers provide the count of massive stars on top, of young PMS stars in the middle and of older PMS object at the bottom of each cell. Since in this field there are a total of 55 massive stars ( $> 15 M_{\odot}$ ) and 350 young PMS stars, on average one would normally expect in each cell about 6 times more young PMS objects than massive stars of similar age, but as the figure shows this is not always the case. On this basis, assuming Poisson statistics, we note at least two regions with many



**Figure 4.** Panel a): relative locations of young PMS stars (darker circles, red in the online version), old PMS stars (lighter circles, yellow in the online version) and massive MS stars (pentagrams, blue in the online version). Panel b): after placing a uniformly spaced grid on panel a), we have counted the number of stars of each type falling into cells of  $25''$  on a side. The corresponding counts are listed in each cell, with the number of massive stars on top, the number of young PMS stars in the middle and that of older PMS object at the bottom of each cell. See text for the meaning of the background colours of the cells.

PMS stars where the observed absence of massive stars has a probability of less than 5 % to occur by chance. They are centered around  $(+60'', +25'')$  and  $(-40'', +70'')$ . This condition is true for the individual cells with darker shade (darker pink in the online version), while for the light-shaded cells in their vicinities (lighter pink in the online version) the condition still applies if they are combined with neighbouring cells of the same or darker colour.

This simple statistical test proves that the observed paucity of massive young stars in these two rather wide areas is significant at a  $2\sigma$  level, at least. In fact, since our photometric completeness is worse in the most central regions (see Sabbi et al. 2007), the paucity of massive young stars is even more pronounced there. A very similar result has been recently found by Cignoni et al. (2011), who analysed the ratio of massive MS stars and low-mass PMS objects within the individual sub-clusters detected by Sabbi et al. (2007) in this region. Although the identification of PMS objects in the work of Cignoni et al. (2011) is purely based on their broad-band colours and magnitudes, and as such can in principle be affected by interlopers and field objects, these authors conclude that the PMS stars in the regions corresponding to our pink cells in Figure 4b are over-represented with respect to massive stars, for a typical IMF.

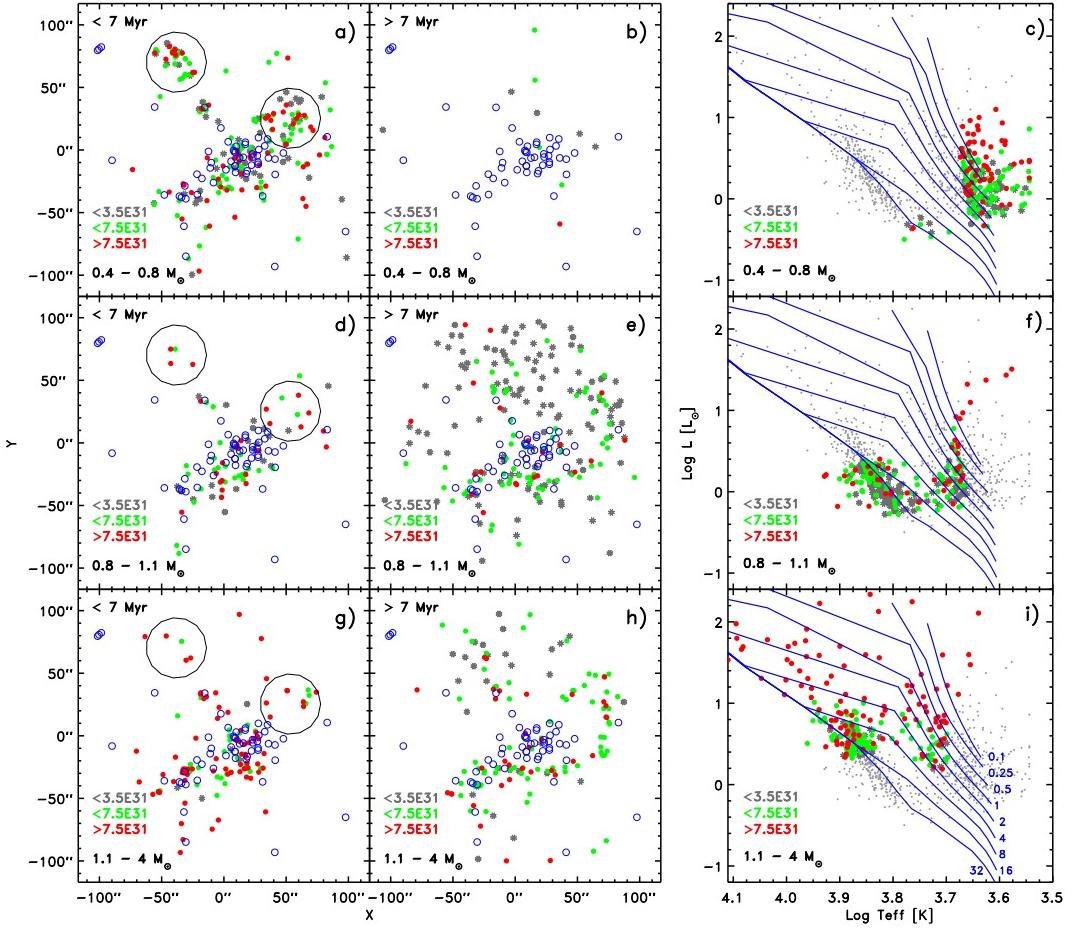
Similarly, one can find in Figure 4b several cells (shaded in darker green in the online version) where the number of young PMS objects falls below the 5 % Poisson probability expected from the number of massive stars. Some of these cells are located at the centre of NGC 346, where crowding and photometric incompleteness make it more difficult to detect fainter PMS stars, so the statistical significance of our non detection of low-mass stars is lower. However, most of the isolated massive stars are located in the outer regions of the cluster, where photometric completeness and crowding are not a concern. It is possible that these objects are not cluster members, but the fact that they are not surrounded by PMS stars of similar age remains puzzling and might imply that they have been

displaced from their formation region due to dynamical interactions, such as in the case of star 30 Dor 016 (Evans et al. 2010).

A possibility would be that these massive objects were the lower-mass companions of disrupted binary systems in which the primaries have already ended their evolution. The radial velocity study of NGC 346 by Evans et al. (2006) suggests that at least 1/4 of the massive stars are in binary systems. The typical projected separation of the isolated massive stars from the centre of NGC 346 is of order  $2'$  or  $\sim 35$  pc. Given the young ages prevalent in NGC 346 (less than 3 Myr), none of the youngest generation stars could have produced runaways. Very few isolated massive stars may indeed be runaways from binary systems if they were part of a  $\sim 15$  Myr old population, such as the one associated with the subcluster SC-16 (Sabbi et al. 2007) and corresponding to the three massive objects in the upper left corner of Figure 3 at  $(-100'', +80'')$ . In this case, runaway stars could cross the entire field of, say,  $2'$  or  $\sim 35$  pc moving at a velocity of about  $3 \text{ km s}^{-1}$  for about 10 Myr.

This however seems hardly to be the case for the objects marked by circles in that figure. Firstly, none of them has an age in excess of 7 Myr, according to our photometry and to the spectroscopy of Evans et al. (2006) for the objects in common with their catalogue. Secondly, the fact that there are only three massive stars in the direct vicinity of the  $\sim 15$  Myr cluster would require that most massive stars were in binary systems and that almost all secondaries have moved away from it: this explanation appears rather contrived and seems to require a very unlikely occurrence. Therefore, we have to accept that the lack of massive stars associated with a number of PMS star clusters simply reflects a genuine property of star formation in those parts of the the NGC 346 complex.

In summary, from the analysis of Figure 4 we can conclude in a more quantitative way that there is little or no spatial correlation between the position of young massive objects and that of PMS stars of similar age, except for the centre of NGC 346, and that the two populations of older and younger



**Figure 5.** Spatial distribution and position in the H–R diagram of all our bona-fide PMS stars, as a function of their age, mass and  $L(\text{H}\alpha)$  luminosity. Objects are sorted according to their age ( $< 7$  Myr or  $> 7$  Myr), to their mass ( $0.4 - 0.8 M_{\odot}$ ,  $0.8 - 1.1 M_{\odot}$  and  $1.1 - 4 M_{\odot}$ ) and to their  $\text{H}\alpha$  luminosity ( $< 3.5 \times 10^{31}$  erg s $^{-1}$ ,  $< 7.5 \times 10^{31}$  erg s $^{-1}$  and  $> 7.5 \times 10^{31}$  erg s $^{-1}$ , respectively grey asterisks, green dots and red dots in the online version) as per the legends shown in each panel. The small circles (blue in the online version) indicate the positions of the 55 young massive stars already shown in Figures 3 and 4a. The two large circles in Panels a), d) and g) refer to the regions described in the text. As for the H–R diagrams, the solid lines correspond to PMS isochrones from the Pisa group for metallicity  $Z = 0.002$  and ages in Myr as indicated in panel i) with a constant logarithmic step (factor of 2). The small dots correspond to stars with masses outside of the range indicated in each panel.

PMS objects have rather different distributions (except again possibly for the regions near the cluster's centre). This implies that the stellar MF varies considerably across the field, as Cignoni et al. (2011) have recently suggested. Therefore, if the MF is sampled over a limited region, its shape will not be statistically representative of the entire cluster. As we discuss in the next section, this has profound implications for the concept of IMF.

#### 4. UNIFORMITY OF THE MASS FUNCTION

Before proceeding to study the MF of PMS stars, we must consider the possible selection effects inherent in our measurements and how they could affect our analysis of the MF. For this purpose we summarise most of the relevant information in Figure 5, to which we will refer throughout this section. Shown in the figure are the spatial distributions and positions in the H–R diagram of all our bona-fide PMS stars, as a function of their ages, masses and  $L(\text{H}\alpha)$  luminosities as measured in Paper II. As before, we split objects into two age groups, younger or older than 7 Myr, while for the mass we use three bins, namely  $0.4 - 0.8 M_{\odot}$ ,  $0.8 - 1.1 M_{\odot}$  and  $1.1 - 4 M_{\odot}$ . We also use symbols of different colours (most easily discernible

in the online version of the paper) to identify stars with different  $\text{H}\alpha$  luminosities, as indicated by the legends. In all panels the small open circles refer to the positions of the same 55 young massive stars already shown in Figures 3 and 4a. As for the H–R diagrams, the solid lines correspond to PMS isochrones from the Pisa group (Degl'Innocenti et al. 2008; Tognelli et al. 2011) for metallicity  $Z = 0.002$  and ages as indicated in panel i) with a constant logarithmic step (0.3 dex corresponding to a factor of two in age). Since the photometric uncertainty is typically smaller than the separation between neighbouring isochrones, with the interpolation procedure explained in Section 2 we are able to assign relative ages with an accuracy of better than a factor of two, typically of order  $\sqrt{2}$ .

A first obvious selection effect, which will however not affect our determination of the MF of young PMS stars, is revealed by the paucity of PMS objects in the range  $0.4 - 0.8 M_{\odot}$  and age  $> 7$  Myr. This is due to the detection limit of our photometry at  $\sim 0.5 L_{\odot}$ .

Another interesting characteristic apparent from this figure, and already partly seen in Figures 3 and 4b, is the compact dis-

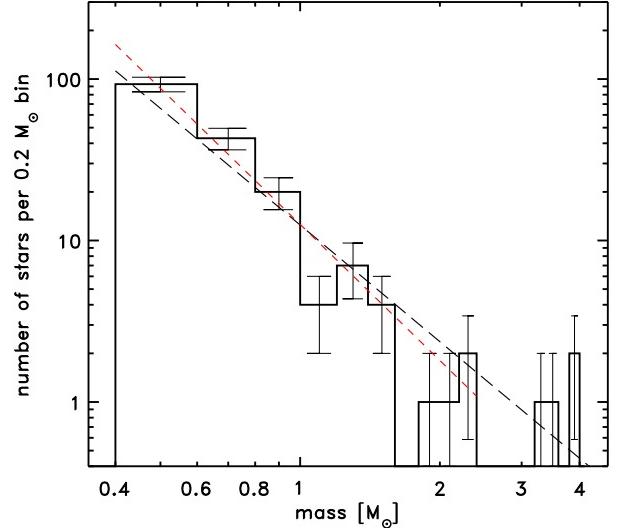
tribution of older PMS stars of all masses along the gaseous rim of the southern arc. The fact that the majority of these objects are rather luminous ( $L(H\alpha) > 7.5 \times 10^{31} \text{ erg s}^{-1}$ ) confirms that they are not artefacts due to the gas rim itself, as already discussed in Section 3.

To illustrate the extent of the MF variations present in this field, we start from panel a), where the two conspicuous groups of young low-mass ( $0.4 - 0.8 M_{\odot}$ ) PMS objects already seen in Figure 4 are visible around  $(+60'', +25'')$  and  $(-40'', +40'')$ , as indicated by the large circles with a radius of  $\sim 25''$  or  $\sim 7.3 \text{ pc}$ . Interestingly, very few objects are found in the same regions in panels d) and g), where equally young stars with masses of respectively  $0.8 - 1.1 M_{\odot}$  and  $1.1 - 4 M_{\odot}$  are shown. In particular, in panel a) there are 36 and 41 PMS stars in these regions, whereas 4 and 8 are found in panel d) and 4 and 9 in panel g), respectively. Based on the number of stars inside the circles in panel a) and assuming a power-law MF of the type  $dN/dm \propto m^{\alpha}$  with  $\alpha = -2.0 \pm 0.2$ , as typically observed in Galactic star forming regions (De Marchi, Paresce & Portegies Zwart 2010), one would expect respectively 11 and 13 objects inside the circles in panel d) and 12 and 14 in panel g). These values are considerably larger than the numbers observed, particularly for the region at  $(+60'', +25'')$ . If we were to derive the slope of the MF in the mass range  $0.4 - 4 M_{\odot}$  from the ratio of the number of stars occupying the same region in the three panels, we would obtain a rather steep, MF with  $\alpha = -3.1 \pm 0.3$  (respectively  $-2.8 \pm 0.3$  in the first region and  $-3.6 \pm 0.4$  in the second). Note that the true MF slope is most likely even steeper, owing to the fact that our smaller mass bin is subject to some incompleteness, as mentioned above, even though the completeness of our photometry is well above 50 % for all but a handful of PMS stars (see Paper II).

Although instructive, the comparison between panels a), d) and g) carried out in this way is subject to some bias. We are using the relative number of stars in different mass bins to characterise the shape of the MF, but the objects that we consider are only those undergoing active mass accretion as witnessed by excess  $H\alpha$  emission. This necessarily introduces some selection effects because more massive stars reach the MS more quickly than lower-mass objects (e.g. Palla & Stahler 1993; see also Paper II) and it becomes increasingly more difficult to derive an accurate age for them. If these objects are associated with older ages, they could be systematically underrepresented in our sample, thereby causing a spurious steepening of the MF.

A possible way to avoid these effects would be to limit the mass range for the analysis, i.e. to consider only panels a) and d) since none of the objects in the mass range  $0.4 - 1.1 M_{\odot}$  is expected to have reached the MS at an age of  $< 7 \text{ Myr}$ . Alternatively, one could limit the age range and only consider very young stars, e.g. those with  $< 1 \text{ Myr}$ , which are all in the PMS phase over the entire mass range considered here ( $0.4 - 4 M_{\odot}$ ). This second approach has the advantage of providing more specific information on the IMF and we will therefore follow it.

Interestingly, however, even when restricting our analysis to stars younger than 1 Myr we still find a very steep MF: there are in total 35 objects with this age in the two reference areas of panel a), but only two objects are found in each of the corresponding regions in panel d) and g). The implied MF slope in the range  $0.4 - 4 M_{\odot}$  remains very steep, namely  $\alpha = -4.3 \pm 0.5$ . One could argue that, if the areas that we are



**Figure 6.** Mass function of PMS stars with age  $< 1 \text{ Myr}$ . The short-dashed line is the best power-law fit in the mass range  $0.4 - 2 M_{\odot}$  and corresponds to  $\alpha = -2.8 \pm 0.2$ . The long-dashed line is the fit over the entire mass range, with  $\alpha = -2.4 \pm 0.4 M_{\odot}$ .

studying are too small, the steep MF slopes that we obtain might be an artefact of small numbers statistics. However, with a projected radius of  $25''$  or  $\sim 7.3 \text{ pc}$ , the circles in panels a), d) and g) are twice as large as the typical size of star forming clusters in the Magellanic Clouds (e.g. Hodge 1988). Therefore, these regions sample a sufficiently large area to be representative of the local conditions of star formation, that in this case appear to be characterised by the paucity of massive stars and correspondingly a rather steep MF slope. A similarly steep MF ( $\alpha = -4 \pm 0.5$ ) was found by Massey (2002) in his study of the field of the Magellanic Clouds, i.e. in regions similarly devoid of massive stars.

A more “typical” value of the MF slope for stars younger than 1 Myr could be derived if we extended our analysis to the entire area covered by these observations, corresponding to  $\sim 60 \text{ pc}$  on a side. In their study of the NGC 346 region, Sabbi et al. (2008) determined the present day MF in NGC 346 from the same observations that we use in this paper. When considering all stars in the field in the range  $0.8 - 60 M_{\odot}$ , they derived a MF slope  $\alpha = -2.43 \pm 0.18$ , very close to the Salpeter (1955) value. When we consider all PMS stars younger than 1 Myr in this field we find a good match with the results of Sabbi et al. (2008) over the common mass range, namely  $0.4 - 4 M_{\odot}$ . This is shown in Figure 6, where the long-dashed line corresponds to  $\alpha = -2.43$  and provides a good fit to the mass distribution of PMS stars younger than 1 Myr. However, we still find a somewhat steeper slope ( $\alpha = -2.8 \pm 0.2$ , short-dashed line) in the mass range  $0.4 - 2 M_{\odot}$ , where the statistics is more robust thanks to the larger number of objects.

In reality, the true MF slope must be slightly shallower than the  $\alpha$  values that we have obtained since we only consider bona-fide PMS stars those showing  $H\alpha$  excess emission at the  $4\sigma$  level or above. As discussed in Paper I and II, the accretion process and with it the  $H\alpha$  luminosity is subject to large variations (a factor of 2 – 3 in a few days; e.g. Fernandez et al. 1995; Smith et al. 1999; Alencar et al. 2001), with the implication that, statistically, not all PMS stars in a given region will show at the same time  $H\alpha$  excess emission above our conservative acceptance threshold. If the fraction

of PMS stars with H $\alpha$  excess emission were constant, considering only these objects would not affect the determination of the MF slope. However, as we will show in a forthcoming paper (De Marchi et al., in preparation), that fraction appears to become smaller when mass and age increase. While age is not an issue in the present case, since we are only considering stars younger than 1 Myr, our objects span about a decade in mass ( $0.4 - 4 M_{\odot}$ ) and in this range variations as large as a factor of 3 are seen in the fraction of PMS stars with H $\alpha$  excess emission. If this effect were taken into account, the slope of the MF over the entire field in the range  $0.4 - 2 M_{\odot}$  would drop slightly, to  $\alpha = -2.0 \pm 0.3$ , a value in line with the typical MF slopes and corresponding uncertainties that are observed in nearby Galactic star forming regions (e.g. De Marchi, Paresce & Portegies Zwart 2010; Bastian, Covey & Meyer 2010).

Nevertheless, even applying this correction to the MFs measured in the two regions discussed above (see the large circles in Figure 5) would still give considerably steeper indices ( $\alpha \simeq -3$ ) than those commonly measured in star clusters. Therefore, the general conclusion that we can draw from this analysis is that there are considerable variations in the shape of the MF of young PMS stars across the field of NGC 346, as witnessed by largely different values of the power-law index  $\alpha$ . These variations remain even when we only consider the MF of stars younger than 1 Myr, which would normally be taken as representative of the IMF.

Since these variations are seen when comparing groups of objects comprising several low-mass stars distributed over the typical size of a stellar cluster (7.5 pc radius), they cannot be ascribed to simple statistical fluctuations. Coupled with the remarkable anti-correlation between massive and low-mass stars of similar age (see Section 3 and Figure 4), this indicates quite convincingly that the formation of high- and low-mass stars requires at least different initial conditions, and might also be governed by different mechanisms. This is also the conclusion recently reached by Cignoni et al. (2011). From the observation that the apparently youngest sub-clusters, i.e. those composed only by stars in the PMS phase, show a deficiency of massive stars, these authors speculate that the IMF may be a function of time, with the youngest sub-clusters not having had sufficient time yet to form more massive objects. As already pointed out by Panagia et al. (2000), while the concept of IMF might be meaningful over large areas where it represents the average result of different star formation processes, its predictive power over smaller scales, characteristic of a specific stellar cluster or association, will have to be seriously reconsidered.

## 5. DISCUSSION

An interesting corollary of the apparent separation between massive star formation sites and regions where moderate/low mass stars form is that, in general, massive stars may turn out to not be “perfect” indicators of active star formation in galaxies. While it is true that regions where massive stars have formed are actively forming stars, it is not necessarily true that those regions identify the places where most of the stars are formed. In fact, integrating over a Salpeter IMF ( $\alpha = -2.35$ ) defined over the range  $0.1 - 150 M_{\odot}$  it is easy to calculate that objects above  $4 M_{\odot}$  represent only about 20% of the total mass that goes into stars. The fraction is even lower in the field of the Magellanic clouds, where Massey (2002) found  $\alpha = -4 \pm 0.5$ .

Our analysis of the NGC 346 observations, as well other

fields in the LMC and SMC (e.g. Panagia et al. 2000; Romaniello, Roberto & Panagia 2004; De Marchi, Romaniello & Panagia 2010; and in preparation) indicates that low mass stars formation appear to run independently of the formation of massive stars. This may be due to the fact that even in a big cloud that is subdivided into smaller sub-units, massive stars can only form inside the larger cells whereas low-mass stars may form readily in smaller cells. If the bulk of the mass in the interstellar medium is not in the form of massive clouds, it is possible that the formation of low mass stars be quite active in regions which are not marked by the presence of massive stars. It is also possible that under suitable conditions this separate channel of low mass star formation be the dominant process to form stars.

Within this scenario, it is clear that measuring the star formation rates of external galaxies, especially in low surface density galaxies, on the basis of massive star diagnostics (be it direct detection of OB stars, optical and radio emission from HII regions, or their secondary far-infrared radiation for highly opaque clouds), may indeed lead to gross underestimates and to misleading results on the nature and the evolution of galaxies.

In order to clarify these issues one should intensively and systematically study regions of local galaxies, selected in an unbiased way, where low mass stars can be individually detected and characterized, so as to determine their physical parameters including mass, luminosity, age and evolutionary status. This can be done not only in our galaxy and, even better, in the Magellanic Clouds in which all stars are approximately at the same distance from us, but also in many other galaxies of the Local Group.

For this purpose, in addition to a number of regions with obvious signs of active star formation, such as the Orion Nebula Cluster (Da Rio et al. 2010b, and in preparation) and NGC 3603 in our Galaxy (Beccari et al. 2010), 30 Dor (De Marchi et al. 2011) and other selected fields in the LMC, and NGC 346 and NGC 602 in the SMC, we are also analysing a sample of fields selected from the Archival Pure Parallel Project<sup>6</sup> that were imaged with the HST-WFPC2 in four broad-band filters (F300W, F450W, F606W, and F814W) and a narrow H $\alpha$  filter (F656N) with a total exposure time of at least 3 orbits, i.e. about 160 minutes (Spezzi et al. 2011). Although these fields are still not completely “random” and “unbiased”, since they were imaged in parallel with long UV spectroscopic observations of OB stars taken with another HST instrument about 5' to 12' away, they still represent a relatively rich sample (about 20 fields in each LMC and SMC) of regions with generally marginal massive star formation. For the future it would be helpful to obtain complementary H $\alpha$  observations of HST archival fields with deep exposures in the  $V$  and  $I$  bands, at least, as well as to target suitably selected new fields in the Milky Way and in the Magellanic Clouds.

Finally, considerable improvements in this field will become possible once PMS evolutionary models are properly calibrated. Even though the models currently available are state of the art, they are not as refined and extensively tested as those for MS stars or post-MS evolution. In particular, absolute PMS ages are difficult to determine due to the lack of independent calibrators. Improvements in these models would make PMS stars even more powerful indicators of how star formation proceeds over time and space.

<sup>6</sup> See <http://archive.stsci.edu/prepds/app/> for details.

## 6. SUMMARY AND CONCLUSIONS

We have studied the properties of the stellar populations in the field of the NGC 346 cluster in the Small Magellanic Cloud, using the results of a novel self-consistent method that provides a reliable identification of PMS objects actively undergoing mass accretion, regardless of their age. We have used the age and other physical parameters measured for these PMS stars to study how star formation has proceeded across time and space in NGC 346 over the past  $\sim 30$  Myr. The main results of this work can be summarised as follows.

1. The 680 identified bona-fide PMS stars show a bimodal age distribution, with two roughly equally numerous populations with median ages of respectively  $\sim 1$  Myr and  $\sim 20$  Myr, although the latter is most likely a lower limit to the true age. The age separation of the two groups is considerably wider than the uncertainties on the relative ages and the scarcity of objects with ages around  $\sim 8$  Myr suggests a lull in star formation at that time.
2. Although, taken at face value, the colours and magnitudes of the older PMS stars are compatible with those of young PMS objects whose light is absorbed and scattered by a high-inclination circumstellar disc, this hypothesis is only viable for a few percent ( $< 5\%$ ) of the stars. This is confirmed by the remarkably different spatial distributions of the two age groups.
3. We set a lower limit to the star formation rate of the ongoing burst of  $\sim 200 M_{\odot} \text{ Myr}^{-1}$ , while at  $\sim 25$  Myr the rate drops by an order of magnitude to  $\sim 20 M_{\odot} \text{ Myr}^{-1}$ . Both values are lower limits since they are based on the number of PMS stars in the range  $0.4 - 4 M_{\odot}$  that were undergoing active mass accretion at the time of the observations.
4. At face value, the strength of the current star formation episode appears to be much higher than that of the one ended  $\sim 8$  Myr ago, while the total integrated output of the two episodes is rather similar. However, since photometric uncertainty does not allow an age resolution of better than a factor of  $\sim \sqrt{2}$ , we cannot establish how many bursts took place between 8 and 30 Myr ago, nor their duration. If there was just one short burst, the star formation strength might have been comparable to or even higher than that of the current episode.
5. Except for the regions near the centre of NGC 346, the stars belonging to the two generations have markedly different spatial distributions. A good fraction ( $\sim 1/3$ ) of the older generation occupies an arc-like gas structure to the south and west of NGC 346 that had been previously interpreted as the ionisation front caused by the OB stars at its centre. Although the morphology of the arc could have suggested a case of triggered star formation, this is clearly not a viable option since the central massive stars are at least 10–20 Myr younger than the objects on the arc and cannot have triggered their formation.
6. The compact distribution of older PMS stars along the arc-like structure suggests that they have formed there from the gas that is still visible and have not (yet) been affected by the massive OB stars at the centre of

NGC 346. This picture is consistent with the very low velocity dispersion ( $< 3 \text{ km s}^{-1}$ ) of the ionised gas measured in this field from high-resolution echelle spectroscopy.

7. Except for the most central regions of NGC 346, we find no correspondence between the positions of young PMS stars and massive O-type stars of similar age, suggesting that the conditions (and possibly also the mechanisms) for their formation must be rather different. Furthermore, the mass distribution of similarly aged stars shows large variations across the region. We conclude that, while on a global scale it makes sense to talk about an initial mass function, this concept is not meaningful for individual star forming clumps.
8. It is possible that a large number of low-mass stars are forming in regions where massive stars are not present and, therefore, they remain unnoticed. For certain low surface density galaxies this might be the predominant way of star formation, which would imply that their total mass based on the luminosity can be severely underestimated and that their evolution is not correctly understood.

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